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Impact of complementary irrigation on soil properties in the Argentine Pampas

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ABSTRACT

The growing application of complementary irrigation in extensive agricultural systems in the Pampas region (Argentina) has increased the frequency of disturbed soil cases. Irrigation management requires appropriate indicators for decision-making in order to avoid disturbance in soil quality. Among these indicators, the use of the sodium adsorption ratio adjusted by the dilution factor (SARdf), which considers the contributions of irrigation water and rainfall during the period projected, could be a sensitive tool. Based on studies conducted under extensive conditions of agricultural production, the objectives of this work were to (i) quantify the changes in the soil chemical and physical properties caused by the use of complementary irrigation with sodium bicarbonate water; (ii) establish relationships between the changes in the chemical and physical properties of the soil; (iii) validate the use of SARdf as a tool to help manage complementary irrigation; and (iv) identify the threshold values to be considered when monitoring and analyzing the evolution of soil properties in areas under complementary irrigation. Twenty-three sites under dryland and irrigated conditions were evaluated. With increasing SARdf, an increase was also recorded in surface bulk density ($r = 0.59$), subsurface bulk density ($r = 0.50$), electrical conductivity ($r = 0.30$; 0.41), pH ($r = 0.56$; 0.70) and exchangeable sodium ratio (ESR) ($r = 0.45$; 0.77), measured in the layers up to 0.10 m and up to 0.20 m in depth. The ESR was evaluated as a sensitive indicator of the effects of irrigation on the physical and chemical properties of soils. In the predominant Typic Argiudoll conditions of the Pampas region, it is advisable to avoid the complementary application of water with a SAR dilution factor greater than 3.0. This threshold value was associated with a $> 60\%$ reduction in basic infiltration. In climate change scenarios, the use of SARdf can help plan the proper management of complementary irrigation.

1. Introduction

Complementary irrigation has made it possible to increase and stabilize crop yields in humid and sub-humid regions (Pilatti et al., 2006; Mon et al., 2007). In the Pampas region (Argentina), irrigation has corrected crop deficiencies in periods when rainfall and the water cumulated in the soil are lower than crop requirements. In general, between 50 and 200 mm of irrigation water per crop has been reported (Lavado, 2009). In this region, underground water is the most common source of irrigation water, and it is characterized by its high content of sodium bicarbonate (Galindo et al., 2007). In the Pampas region, complementary irrigation is a recently generalized agricultural practice. It is

Abbreviations: Ca, exchangeable calcium; EC, electrical conductivity; CEC, cation exchange capacity; Bd 0–5, bulk density from 0 to 0.05 m; Bd 10–15, bulk density from 0.10 to 0.15 m; DF, dilution factor; HCO_3, bicarbonate; K, exchangeable potassium; Mg, exchangeable magnesium; OM, organic matter; Na, exchangeable sodium; ESR, exchangeable sodium ratio; SAR, sodium adsorption ratio; SARdf, sodium adsorption ratio adjusted by the dilution factor; RP 0–5, average resistance penetration in the layer from 0 to 0.05 m; RP 10–15, average resistance penetration in the layer from 0.10 to 0.15 m; RP 15–20, average resistance penetration in the layer from 0.15 to 0.20 m; RP 5–10, average resistance penetration in the layer from 0.05 to 0.10 m; RPmax 5–40, maximum resistance penetration in the layer from 0.05 to 0.40 m; IR, basic infiltration rate.

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carried out using waters with moderate to high sodium levels and the cumulated irrigation vary depending on the water balances (Alvarez et al., 2021). Averaged over the last 25 years, annual rainfalls ranges between 600 and 1000 mm (Alvarez et al., 2021).

The degradation of the physical and chemical properties of Typic Argiudoll soils has been attributed to the effect of complementary irrigation. For example, in a plot in the center of the Pampas region, Torres Duggan et al. (2012) observed increases in the levels of exchangeable sodium ratio (ESR), pH and electrical conductivity (EC) in irrigated areas in comparison with dryland. In the same region, increases in ESR, EC and pH were observed in the first soil layer after 11 years of irrigation with sodium bicarbonate water, with a sodium adsorption ratio (SAR) of 10.6. In this experiment, the initial values of ESR increased by 400% after four years and by 600% after 11 years under complementary irrigation (Andriulo et al., 1998). In the southeast of the Pampas region, Costa and Aparicio (2015) reported increases in ESR, pH and EC levels, as well as a decrease in basic infiltration levels.

To adjust irrigation management and reduce its negative effects on soil properties, some methodologies have been proposed, such as the use of cumulative irrigation according to the quality of the water used and the frequency of irrigation. The Riverside and FAO classifications established risks of salinization and sodification according to the levels of EC and SAR (Ayers and Westcot, 1987). These classifications were found to be adequate for conditions in which irrigation water is the main source of water for crops. However, there is little information about adequate water quality criteria under a combination of irrigation with high SAR water and rainfall during the crop cycle (Suarez et al., 2006; Suarez et al., 2008). Rainfall generates wetting and drying effects that may cause aggregate decomposition and reduce infiltration rates, while prolonged drying periods allow aggregate formation and the development of larger pores (Levy et al., 1997). The larger pores have been described as most relevant in conditions of reduced infiltration rates due to the effect of complementary irrigation (Costa and Aparicio, 2015). The direct application of infiltration studies according to SAR and EC levels in irrigation water is uncertain given the omission of the wetting and drying cycles (Suarez et al., 2008).

The classification of water for complementary irrigation developed by Costa and Aparicio (2015) considers the SAR of irrigation water adjusted by the dilution factor. They established the dilution factor by relating the cumulative irrigation water and the total cumulative water. The total cumulative water included both rainfall and complementary irrigation. In addition, these authors determined a SAR threshold adjusted by the dilution factor (SARdf), below which they did not observe significant infiltration differences in comparison with dryland. The SARdf threshold was established at 3.5 and validated under field conditions and with data from experiments in pots. The water quality of the sites under field conditions used for the validation ranged from 0.8 to 2.0 dS m^{-1} EC and from 10.0 to 15.1 SAR. The use of SARdf may contribute to irrigation management decisions. However, it is necessary to validate the observed results in a greater range of water quality and cumulative irrigation.

In addition, the effects of complementary irrigation on the physical properties of the soil have been evaluated by considering infiltration and bulk density as diagnostic variables (Costa and Aparicio, 2015; Torres Duggan et al., 2012). These evaluations require agronomists with experience and training to obtain quality data. The soil chemical properties incorporated into soil sampling for crop nutrition diagnoses, associated with bulk density and infiltration, are necessary for monitoring areas under irrigation. In the Pampas region, ESR levels greater than 5.26% showed a significant decrease in infiltration and an increase in bulk density (Costa and Aparicio, 2015).

For Typic Argiudoll soils in the Argentine Pampas region, the objectives of this study were to (i) quantify the changes in the chemical and physical properties of the soils resulting from the use of complementary irrigation with sodium bicarbonate water; (ii) establish relationships between changes in the chemical and physical properties of the soils; (iii) validate the use of SARdf as a tool to help manage complementary irrigation; and (iv) identify the threshold values to be considered when monitoring and analyzing the evolution of soil properties in areas under complementary irrigation.

2. Materials and methods

2.1. General description and experimental design

The experimental sites were 23 plots located in the southeast of the Pampas region (Argentina) (Fig. 1). The cumulative irrigation over the last 25 years in these sites ranged from 180 to 2485 mm. The average SAR of irrigation water ranged from 0.9 to 18.9. The average annual rainfall varied from 850 to 1045 mm. In all cases, complementary irrigation was performed by sprinkling (Table 1).

The dryland and irrigated conditions were evaluated by considering the sites as repetitions. The dryland treatment corresponded to the non-irrigated corners of the lot, whereas the irrigation treatment corresponded to the irrigated area. In all cases, soil type, crop sequences that included wheat, barley, corn, soybean and sunflower, and crop management (tillage, fertilization, weed and diseases protection) were the same in both dryland and irrigated conditions. The soils that predominated were Typic Argiudols with a superficial horizon with a clay loam texture (Soil Survey Staff, 2022), well drained, developed in fine loam loessic sediments on a calcareous crust of regional extension, not saline, not alkaline and with slopes of 1–3%.

According to the experimental design used by Costa and Aparicio (2015), the SARdf was calculated for each irrigated site by integrating all the years of irrigation and rainfall history. The SAR and dilution factor (DF) formulas are defined as follows:

$$SAR = \frac{Na^{+}}{\sqrt{[(Ca^{2+} + Mg^{2+})/2]}}$$

where Na^{+}, Ca^{2+}, and Mg^{2+} are the concentrations in mmolc L^{-1} of sodium, calcium, and magnesium ions.

$$DF = \frac{I}{(R + I)}$$

where DF is dilution factor, *I* is cumulative irrigation and *R* is cumulative rainfall.

Applying this dilution factor to the Na^{+}, Ca^{2+} and Mg^{2+} values of irrigation water, SARdf was calculated using the following equation:

$$SARdf = \frac{Na^{+}DF}{\sqrt{[(Ca^{2+}DF + Mg^{2+}DF)/2]}}$$

where Na^{+}, Ca^{2+}, and Mg^{2+} are the concentrations in mmolc L^{-1} of sodium, calcium, and magnesium ions and *DF* is the dilution factor.

The SARdf values were calculated for different cumulative periods up to the current date. The maximum SARdf value was considered to characterize each site. This was done in order to take into account the dilution effect of rainwater on the salt input from irrigation (Costa and Aparicio, 2015).

2.2. Irrigation water quality

Cumulative rainfall and irrigation were recorded for each evaluation site over the past 25 years. Water samples were taken during the operation of the irrigation equipment. The samples were collected at distant positions from each pivot center (between 50 m and 800 m, depending on pivot size) and then combined (6 subsamples). Samples were taken in the last crop cycle from all evaluated sites. In all sites, 1 or 2 analyses from previous periods were available, and it was verified that the SAR variation between results was less than 3%. The water samples were analyzed using the methodologies proposed by SAMLA (2004) for the

Fig. 1. Map of the 23 plots locations in the southeast of the Pampas region (Argentina).

Table 1
Surface texture (0 to 0.2 m), water input over 25 years and average irrigation water quality in 23 sites with complementary irrigation in the Pampas region (Argentina). Irrigation water quality: electrical conductivity (EC), calcium (Ca), magnesium (Mg), sodium (Na) and bicarbonate (HCO_3) levels and sodium adsorption ratio (SAR).

Site	Soils		Water input		Irrigation water composition					
	Clay	Sand	Irrigation	Rainfall	EC	Ca	Mg	Na	HCO_3	SAR
	g kg^{-1}		mm		dS m^{-1}	cmol$_c$ l^{-1}				
1	270	340	710	21,941	1.18	0.023	0.017	1.061	0.797	17.0
2	270	340	1489	21,950	1.12	0.035	0.029	0.935	0.736	11.7
3	340	370	885	21,900	1.12	0.035	0.029	0.935	0.736	11.7
4	290	420	488	21,940	1.18	0.023	0.017	1.061	0.797	17.0
5	310	320	1594	21,890	1.18	0.023	0.017	1.061	0.797	17.0
6	270	360	302	21,895	1.18	0.023	0.017	1.061	0.797	17.0
7	270	420	431	21,910	1.21	0.022	0.020	0.696	0.377	10.7
8	290	320	500	22,498	1.17	0.027	0.022	0.897	0.637	12.9
9	260	390	500	22,450	1.17	0.027	0.022	0.897	0.637	12.9
10	270	360	500	22,420	1.17	0.027	0.022	0.897	0.637	12.9
11	296	459	1200	21,210	0.45	0.035	0.066	0.457	0.754	4.5
12	322	430	600	21,250	0.45	0.035	0.066	0.457	0.754	4.5
13	247	429	600	21,230	0.70	0.042	0.032	0.611	0.754	7.1
14	334	391	2485	21,240	0.75	0.070	0.058	0.535	0.754	4.7
15	220	360	1198	26,130	0.83	0.083	0.065	0.585	0.704	4.8
16	270	330	1307	26,135	0.72	0.135	0.140	0.161	0.592	0.9
17	240	350	828	26,135	0.84	0.075	0.058	0.596	0.610	5.1
18	260	330	430	26,100	1.00	0.053	0.037	0.861	0.739	9.1
19	303	350	680	22,875	2.38	0.048	0.082	2.160	0.916	18.9
20	303	350	140	22,840	2.38	0.048	0.082	2.160	0.916	18.9
21	395	385	600	21,250	1.50	0.070	0.043	1.478	0.967	13.9
22	273	424	600	21,260	1.50	0.070	0.043	1.478	0.967	13.9
23	257	428	180	24,500	1.50	0.070	0.043	1.478	0.967	13.9
Average	285	376	793	22,755	1.16	0.048	0.044	0.979	0.754	11.3
Standard deviation	37	41	528	1709	0.47	0.027	0.029	0.490	0.137	5.1

following parameters: EC, Ca, Mg, Na, HCO_3 and SAR.

The irrigation water used in the evaluated sites exhibited EC and SAR values similar to those observed by Angelini et al. (2022) in data integration in the Pampas region. These authors found EC ranges from 0.5 to 1.3 dS m^{-1} and average SAR ranges by zone from 7.0 to 13.0. For the conditions evaluated in this study, the irrigation water used was classified according to Riverside and FAO (Ayers and Westcot, 1987) as moderate to high risk of salinization and as moderate-high and very high risk of sodification (Table 1).

2.3. Evaluations of soil chemical and physical properties

The chemical properties were evaluated in the layers from 0 to 0.1 m and from 0 to 0.2 m, by taking one sample composed of 20 subsamples for each site and soil layer. The following parameters were determined in the last crop cycle: organic matter (Nelson and Sommers, 1996); content of exchangeable cations (calcium, potassium, magnesium and sodium) by atomic absorption; cation exchange capacity (CEC); pH; electrical conductivity (EC); basic infiltration rate (IR; Soil Quality Institute, 1999; n = 4); bulk density from 0 to 0.05 m (Bd 0–5) and from 0.10 to 0.15 m (Bd 10–15) by the cylinder method (n = 3); resistance to penetration with a hydraulic penetrometer with a 60° tip (n = 10); and soil structure status by adapting the drop shatter test by Peralta (2008); Díaz-Zorita et al., 2002; Mueller et al. 2013). The modification of the drop shatter test consists in quantifying the weight of the soil fragments grouped by size. Then, the proportion of each soil fragment grouped by size was evaluated in relation to the total soil.

In the layers from 0 to 0.1 m and from 0 to 0.2 m, the ESR was calculated according to

$$ESR = \frac{Na^{+}}{CEC}100$$

where Na^{+} is exchangeable sodium and CEC is cation exchange capacity.

2.4. Statistical analysis

It was verified that the variables analyzed had a normal distribution using the Kolmogorov-Smirnov test and basic diagnostic graphs. Within each site, the means of each variable for dryland and irrigated were compared using the *t*-test. When the variable was evaluated at different depths, the comparison was made within each depth. In order to perform each pair of comparisons, the homogeneity of the variance was previously evaluated using the F test. When the variances were not homogeneous ($p > 0.05$), the Satterthwaite correction was used. Finally, correlation analyzes were carried out between variables of soil properties and between variables associated with complementary irrigation and soil properties (Pearson, $p < 0.10$).

3. Results and discussion

3.1. Effects of complementary irrigation on soil chemical and physical properties

The dryland soil properties are representative of the Argentine Pampas region. The OM averages were 5.86% in the 0–0.10 m layer and 5.50% in the 0–0.20 m layer. The pH levels were 5.71 in the 0–0.10 m layer and 5.63 in the 0–0.20 m layer. The EC was 0.16 dS m^{-1} in the 0–0.10 m layer and 0.13 dS m^{-1} in the 0–0.20 m layer. These results are consistent with evaluations in Typic Argiudolls in dryland and with similar crop rotations in the region (Costa and Aparicio, 2015).

Average soil properties in rainfed and irrigated areas in the Argentine Pampas region are shown in Table 2. The EC levels of the soils were low (ranging from 0.09 to 0.35 dS m^{-1}). Complementary irrigation increased EC levels in the 0–0.20 m soil layer by an average of 35%. These increases are in agreement with or slightly lower than those observed by other authors in the Pampas region (Andriulo et al., 1998; Torres Duggan et al., 2012; Costa and Aparicio, 2015). The EC values in irrigated areas were lower than 2 dS m^{-1}, and no salinization was observed according to the Riverside classification.

Complementary irrigation increased the ESR in the soils by 84% in the 0–0.10 m layer and by 175% in the 0–0.20 m layer in comparison with dryland soils (Table 2). The maximum ESR values observed under irrigation were 5.79% in the 0–0.10 m layer and 5.53% in the 0–0.20 m layer. The minimum and maximum increases (minimum 30%, maximum 576%) were observed in the 0–0.10 m soil layer and were associated with sites with lower and higher cumulative irrigation respectively. Coinciding with EC, the increases observed in the ESR were similar to or slightly lower than those reported by other authors (Andriulo et al., 1998; Torres Duggan et al., 2012; Costa and Aparicio, 2015). The maximum ESR levels reached were lower than those reported by Torres Duggan et al. (2012) and Costa and Aparicio (2015) and lower than the limit of 15%. No sodification was observed based on the Riverside classification. However, according to Pilatti et al. (2006) and Costa and Aparicio (2015), who studied Typic Argiudoll soils in the Pampas region, the sodium levels observed in the present study have negative effects on soil structure and, therefore, on soil porosity. The pH increased significantly in irrigated areas by about 0.5 units in both the 0–0.10 m and 0–0.20 m soil layers. These increases were also observed by other authors in the region (Torres Duggan et al., 2012; Costa and Aparicio, 2015) (Table 2).

Organic matter levels were higher in dryland than in irrigated areas (8.40% increases). The CEC did not show differences between dryland and irrigated areas in the first 0.10 m of the soils. However, a higher CEC was observed in irrigated areas in the first 0.20 m of the soils. These differences could be attributed to the higher pH levels noted in irrigated areas in comparison with dryland areas.

The main effects of complementary irrigation on the physical soil properties were observed in increases in surface and subsurface bulk density, reduction in basic infiltration and degradation of soil structure evidenced by a greater proportion of large soil fragments, as measured by the drop shatter test. Complementary irrigation increased surface and subsurface bulk density by 6% and 5%, respectively (Fig. 2a). Basic infiltration decreased by 52% in irrigated areas. On average, infiltration was 114 mm h^{-1} in dryland areas and 54 mm h^{-1} in irrigated areas (Fig. 2b). The increases in bulk density and the reduction due to infiltration observed were greater than those reported by Torres Duggan et al. (2012), who found no differences between dryland and irrigated areas, with surface bulk density ranging from 1.25 to 1.28 Mg m^{-3} and infiltration ranging from 145 to 215 mm h^{-1}.

Irrigated areas had a higher proportion of large soil fragments (>0.1 m) and medium-sized soil fragments (between 0.1 and 0.05 m) than dryland areas, while the proportion of smaller soil fragments (<0.05 m) was lower in irrigated than in dryland areas (Fig. 2c). Dryland areas showed a predominance of granular structural types or small subangular blocks at the time of evaluation, coinciding with a higher proportion of soil fragments with diameters lower than 0.05 m after the drop shatter test. The soil fragments greater than 0.05 m after the evaluation exhibited characteristics similar to the structures described as massive type by De Battista et al. (1993). The observed results, with a higher proportion of larger soil fragments in irrigated areas, are associated with conditions of soil structure degradation in comparison with areas without complementary irrigation (Peralta, 2008). Similar diagnoses of structure degradation due to the incorporation of complementary irrigation were reported by Pilatti et al. (2006), who evaluated the stability of dry and wet aggregates in sites with organic matter levels lower than those of our experiment. In contrast, under conditions with similar organic matter levels, Torres Duggan et al. (2012) evaluated sites with increased ESR due to complementary irrigation and did not observe

Table 2
Average soil properties in 23 dryland and 23 irrigated sites in the Pampas region (Argentina). EC: electrical conductivity; OM: organic matter; Na: exchangeable sodium; CEC: cation exchange capacity; ESR: exchangeable sodium ratio. Standard deviation values are in brackets. The p-value < 0.05 indicates significant differences between dryland and irrigated areas according to the *t*-test for paired data.

Properties	Soil depth					
	0–0.10 m			0–0.20 m		
	Dryland	Irrigation	p-value	Dryland	Irrigation	p-value
pH	5.71 (0.47)	6.11 (0.43)	0.0053	5.63 (0.34)	6.16 (0.52)	0.0002
EC (dS m^{-1})	0.16 (0.06)	0.20 (0.08)	0.1195	0.13 (0.05)	0.18 (0.09)	0.0344
OM (%)	5.86 (1.01)	5.33 (0.68)	0.0412	5.50 (0.98)	5.04 (0.67)	0.0739
Na ($cmol_c$ kg^{-1})	0.36 (0.25)	0.67 (0.31)	0.0008	0.24 (0.07)	0.72 (0.27)	0.0001
CEC ($cmol_c$ kg^{-1})	21.26 (3.47)	21.52 (3.97)	0.8199	19.76 (2.32)	21.61 (3.81)	0.0550
ESR (%)	1.67 (1.13)	3.09 (1.10)	0.0001	1.21 (0.32)	3.33 (0.93)	0.0001

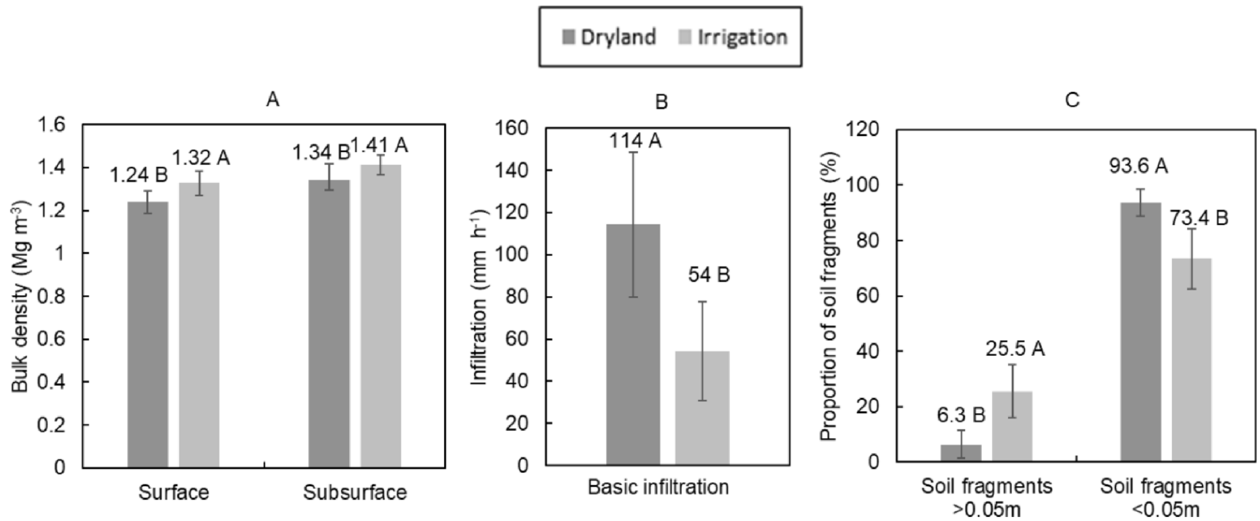

Fig. 2. A: Average surface (0–0.05 m) and subsurface (0.10–0.15 m) bulk density, B: basic infiltration, C: proportion of soil fragments by size corresponding to the drop shatter test, at 23 production sites in dryland and irrigated areas in the Pampas region (Argentina). Different letters indicate differences between dryland and irrigated conditions with $p < 0.10$. Standard deviation of means in error bars.

significant degradation effects on the soil structure through structural stability evaluation.

The ESR in the 0–0.20 m soil layer stood out among the properties studied for its correlation with the chemical and physical properties of the soils. The main soil properties of the Pampas region that have been reported to show changes associated with complementary irrigation are EC, pH, infiltration and bulk density (Torres Duggan et al., 2012; Costa and Aparicio, 2015; Andriulo et al., 1998; Pilatti et al.2006). Under these evaluation conditions, the ESR showed correlation with chemical properties such as EC and pH. In addition, the ESR in the 0–0.20 m layer correlated with the physical properties of the soils. A negative correlation was observed between bulk density and the smallest soil fragments, and a positive correlation was observed between basic infiltration and the smallest soil fragments, as measured by the drop shatter test (Table 3 and Fig. 3). Costa and Aparicio (2015) observed negative effects on soil infiltration at ESR levels greater than 5.26%. In the present work,

Table 3
Correlation analysis of soil properties for 46 cases (23 dryland + 23 with complementary irrigation). Level of significance of the correlation according to p-value. Cell background indicating significant levels of p-value < 0.05 on dark gray, p-value 0.05–0.10 on light gray and p-value > 0.10 on white background. Correlation between colored soil properties according to the level of significance and the sign of correlation. Green background: significant positive correlation; red background: significant negative correlation; white background: non-significant correlation. Bd 0–5: bulk density in the 0–0.05 m soil layer. Bd 10–15: bulk density in the 0.10–0.15 m soil layer. RP 0–5: average resistance penetration in the layer from 0 to 0.05 m. RP 5–10: average resistance penetration in the layer from 0.05 to 0.10 m. RP 10–15: average resistance penetration in the layer from 0.10 to 0.15 m. RP 15–20: average resistance penetration in the layer from 0.15 to 0.20 m. RPmax 5–40: maximum resistance penetration in the layer from 0.05 to 0.40 m. OM: organic matter; EC: electrical conductivity. CEC: cation exchange capacity. ESR: exchangeable sodium ratio.

		Bulk density		Resistance to penetration					Infiltration		Drop shatter test		Soil properties at 0-0.10 m					Soil properties at 0-0.20 m						
Coefficients\p-value		Bd 0-5	Bd 10-15	RP 0-5	RP 5-10	RP 10-15	RP 15-20	Rpmax 5-40	Basic infiltration	Basic infiltration relative to the control	Soil fragments >0.05m	Soil fragments <0.05m	OM	EC	pH	CEC	ESR	OM	EC	pH	CEC	ERS	Sand	Clay
Bulk density	Bd 0-5	1.00	0.001	0.770	0.080	0.020	0.020	0.840	< 0.001	< 0.001	< 0.001	< 0.001	0.190	0.540	0.001	0.790	0.020	0.090	0.550	0.001	0.020	0.001	0.840	0.290
	Bd 10-15	0.47	1.00	0.270	0.810	0.800	0.860	0.880	0.870	0.001	0.010	0.020	0.002	0.360	0.002	0.320	0.001	0.010	0.680	0.004	0.020	< 0.001	0.050	0.180
Resistance to penetration	RP 0-5	-0.04	-0.17	1.00	< 0.001	< 0.001	0.001	0.010	0.270	0.650	0.680	0.920	0.850	0.050	0.110	0.520	0.110	0.770	0.380	0.370	0.390	0.860	0.160	0.700
	RP 5-10	-0.26	-0.04	0.83	1.00	< 0.001	< 0.001	< 0.001	0.002	0.170	0.200	0.130	0.280	0.030	0.070	0.040	0.010	0.350	0.290	0.260	0.020	0.420	0.010	0.930
	RP 10-15	-0.34	-0.04	0.66	0.93	1.00	< 0.001	< 0.001	0.001	0.030	0.020	0.020	0.080	0.070	0.040	0.040	0.002	0.100	0.390	0.240	0.005	0.210	0.020	0.940
	RP 15-20	-0.35	-0.03	0.47	0.80	0.95	1.00	< 0.001	< 0.001	0.010	0.002	0.002	0.050	0.170	0.050	0.030	0.001	0.050	0.460	0.260	0.001	0.050	0.040	0.920
	Rpmax 5-40	0.03	0.02	0.39	0.56	0.54	0.55	1.00	0.040	0.620	0.710	0.600	0.001	< 0.001	0.140	0.001	0.140	0.001	< 0.001	0.010	0.003	0.830	0.140	0.740
Infiltration	Basic infiltration	-0.56	-0.02	0.17	0.44	0.48	0.51	0.30	1.00	< 0.001	0.004	0.005	0.370	0.410	0.030	0.010	0.010	0.200	0.480	0.030	0.005	0.010	0.140	0.160
	Basic infiltration relative to the control	-0.56	-0.48	0.07	0.21	0.32	0.40	0.07	0.50	1.00	< 0.001	< 0.001	0.230	0.160	0.004	0.810	0.010	0.290	0.040	0.002	0.010	< 0.001	0.180	0.280
Drop shatter test	Soil fragments >0.05m	0.56	0.40	0.07	-0.21	-0.38	-0.49	-0.06	-0.45	-0.76	1.00	< 0.001	0.610	0.190	0.030	0.700	0.003	0.810	0.070	0.020	0.030	< 0.001	0.090	0.240
	Soil fragments <0.05m	-0.58	-0.38	-0.02	0.25	0.39	0.48	0.09	0.45	0.76	-0.98	1.00	0.730	0.120	0.050	0.840	0.010	0.840	0.050	0.030	0.060	< 0.001	0.090	0.160
Soil properties at 0-0.10 m	OM	-0.20	-0.45	0.03	-0.16	-0.26	-0.29	-0.46	0.13	0.18	-0.09	0.06	1.00	0.060	< 0.001	0.002	0.280	< 0.001	0.002	< 0.001	0.050	0.160	0.710	0.810
	EC	-0.09	-0.14	0.29	0.31	0.27	0.20	0.61	0.12	-0.21	0.22	-0.26	-0.28	1.00	0.320	0.090	0.260	0.050	< 0.001	0.010	0.020	0.420	0.050	0.750
	pH	0.46	0.44	-0.24	-0.27	-0.31	-0.29	0.22	-0.32	-0.41	0.35	-0.31	-0.51	0.15	1.00	0.990	0.030	< 0.001	0.010	< 0.001	0.020	0.020	0.140	0.080
	CEC	0.04	-0.15	-0.10	-0.30	-0.30	-0.32	-0.47	-0.40	-0.04	0.06	-0.03	0.44	-0.25	0.00	1.00	0.200	0.004	0.003	0.330	< 0.001	0.260	0.020	0.060
	ESR	0.34	0.46	-0.24	-0.39	-0.44	-0.47	-0.22	-0.40	-0.38	0.47	-0.43	-0.16	-0.17	0.32	0.19	1.00	0.440	0.590	0.040	0.010	0.000	0.780	0.180
Soil properties at 0-0.20 m	OM	-0.25	-0.39	0.04	-0.14	-0.25	-0.30	-0.47	0.19	0.16	-0.04	0.03	0.98	-0.29	-0.51	0.42	-0.12	1.00	0.002	< 0.001	0.050	0.390	0.820	0.840
	EC	0.09	0.06	0.13	0.16	0.13	0.11	0.68	0.11	-0.31	0.30	-0.32	-0.44	0.89	0.36	-0.43	-0.08	-0.44	1.00	< 0.001	0.020	0.240	0.090	0.080
	pH	0.47	0.41	-0.14	-0.17	-0.18	-0.17	0.39	-0.32	-0.45	0.37	-0.35	-0.67	0.39	0.86	-0.15	0.30	-0.67	0.60	1.00	0.450	0.010	0.740	0.360
	CEC	0.35	0.33	-0.13	-0.33	-0.41	-0.46	-0.43	-0.41	-0.39	0.36	-0.31	0.29	-0.33	0.34	0.70	0.38	0.30	-0.35	0.11	1.00	0.010	0.230	0.490
	ESR	0.48	0.58	0.03	-0.12	-0.19	-0.29	-0.03	-0.39	-0.64	0.84	-0.81	-0.21	0.12	0.34	0.17	0.67	-0.13	0.18	0.40	0.40	1.00	0.130	0.730
	Sand	0.03	0.29	0.21	0.38	0.34	0.30	0.22	0.22	-0.20	0.28	-0.28	-0.06	0.30	-0.22	-0.34	-0.04	-0.03	0.25	-0.05	-0.18	0.22	1.00	0.870
	Clay	0.16	0.20	0.06	0.01	-0.01	-0.01	0.05	0.21	-0.16	0.19	-0.23	0.04	0.05	0.26	-0.28	-0.20	0.03	0.26	0.14	0.10	-0.05	-0.02	1.00

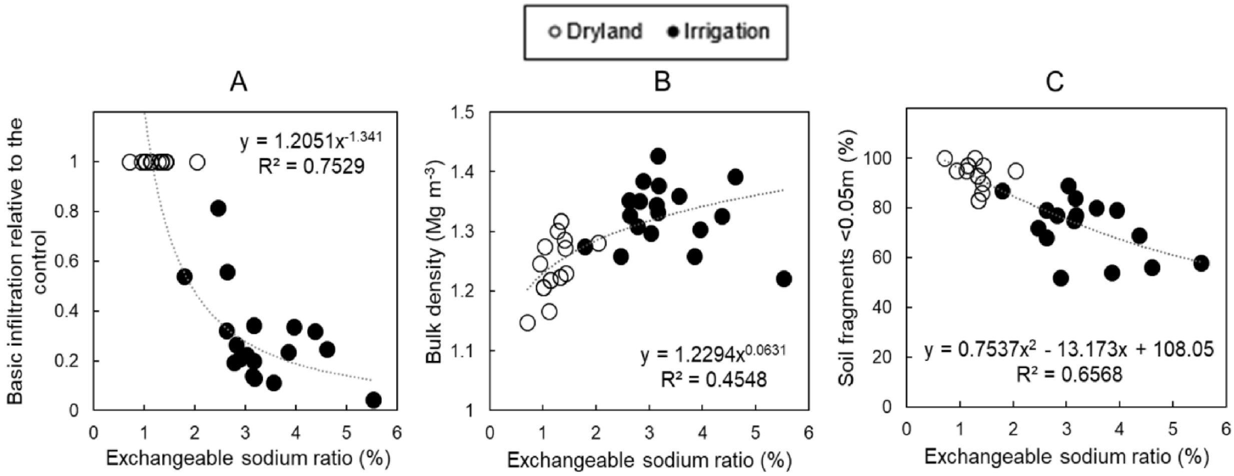

Fig. 3. A: relationship between basic infiltration and the control (dryland); B: bulk density in the 0–0.05 m soil layer; C: proportion of soil fragments smaller than 0.05 m, as measured by the drop shatter test, according to the levels of exchangeable sodium ratio (ESR) in the 0–0.20 m soil layer for 46 cases (23 dryland + 23 irrigated) in the Pampas region (Argentina).

increased bulk density and reduced infiltration were found at ESR levels lower than 5.26% (Fig. 3). For the evaluated conditions, the ESR at 0–0.20 m can be considered a suitable variable for monitoring the effects of irrigation on the chemical and physical properties of soils.

The superficial bulk density also showed association with physical and chemical properties of the soils that have been reported with changes associated with complementary irrigation (Torres Duggan et al., 2012; Costa and Aparicio, 2015; Andriulo et al., 1998). Higher levels of surface bulk density were associated with higher levels of subsurface bulk density, higher resistance to penetration, and higher soil fragments of the drop shatter test (Table 3). In addition, higher levels of surface bulk density were associated with higher levels of ESR and pH, and

Table 4
Correlation analysis of variables associated with complementary irrigation and soil properties. The p-value of correlation with cell background indicating significant levels of p-value < 0.05 on dark gray, p-value 0.05–0.10 on light gray and p-value > 0.10 on white background. Correlation between irrigation and soil properties shown by colors according to the level of significance and the sign of correlation: green background, significant positive correlation; red background, significant negative correlation. Bd 0–5: bulk density in the 0–0.05 m soil layer. Bd 10–15: bulk density in the 0.10–0.15 m soil layer. RP 0–5: average resistance penetration in the layer from 0 to 0.05 m. RP 5–10: average resistance penetration in the layer from 0.05 to 0.10 m. RP 10–15: average resistance penetration in the layer from 0.10 to 0.15 m. RP 15–20: average resistance penetration in the layer from 0.15 to 0.20 m. RPmax 5–40: maximum resistance penetration in the layer from 0.05 to 0.40 m. OM: organic matter; EC: electrical conductivity. CEC: cation exchange capacity. ESR: exchangeable sodium ratio. SARdf: sodium adsorption ratio of irrigation water adjusted by the dilution factor (Costa and Aparicio, 2015).

Soil properties		Irrigation									
		Electrical conductivity		pH		SAR		Cumulated irrigation over 25 years		SARdf	
		Correlation coefficient	p-value	Correlation coefficient	p-value	Correlation coefficient	p-value	Correlation coefficient	p-value	Correlation coefficient	p-value
Bulk density	Bd 0-5	0.31	0.200	0.92	0.080	0.25	0.310	0.46	0.005	0.59	< 0.001
	Bd 10-15	0.18	0.470	0.01	0.990	0.47	0.050	0.34	0.040	0.50	0.002
Resistance to penetration	RP 0-5	0.05	0.850	-0.46	0.540	-0.10	0.690	-0.07	0.680	0.04	0.810
	RP 5-10	0.03	0.910	-0.31	0.690	-0.07	0.770	-0.18	0.300	-0.08	0.660
	RP 10-15	-0.02	0.930	-0.28	0.720	-0.21	0.400	-0.16	0.350	-0.20	0.230
	RP 15-20	0.03	0.900	0.08	0.920	-0.23	0.350	-0.22	0.200	-0.30	0.080
	Rpmax 5-40	0.66	0.003	0.92	0.080	0.24	0.330	-0.04	0.820	0.29	0.090
Infiltration	Basic infiltration	0.10	0.710	-0.31	0.690	-0.11	0.650	-0.68	< 0.001	-0.72	< 0.001
	Basic infiltration relative to the control	0.17	0.510	-0.28	0.720	-0.04	0.890	-0.78	< 0.001	-0.79	< 0.001
Drop shatter test	Soil fragments >0.05m	-0.37	0.120	-0.62	0.260	-0.50	0.030	0.33	0.170	-0.18	0.460
	Soil fragments <0.05m	0.41	0.100	0.30	0.700	0.64	0.010	-0.75	< 0.001	-0.54	0.002
Soil properties at 0–0.10 m	OM	-0.42	0.080	-0.88	0.120	-0.03	0.900	-0.17	0.320	-0.29	0.090
	EC	0.23	0.350	0.51	0.490	-0.08	0.740	0.31	0.060	0.30	0.070
	pH	0.70	0.001	0.99	0.010	0.49	0.040	0.32	0.060	0.56	< 0.001
	CEC	-0.22	0.380	-0.87	0.130	0.09	0.730	0.07	0.700	0.01	0.980
	ESR	0.20	0.440	-0.43	0.570	0.12	0.640	0.40	0.020	0.45	0.010
Soil properties at 0–0.20 m	OM	-0.43	0.080	-0.90	0.100	-0.04	0.870	-0.19	0.270	-0.26	0.130
	EC	0.39	0.110	0.97	0.030	0.03	0.920	0.34	0.040	0.41	0.010
	pH	0.70	0.001	0.95	0.050	0.37	0.130	0.45	0.010	0.70	< 0.001
	CEC	-0.04	0.880	-0.78	0.220	0.34	0.160	0.29	0.090	0.46	0.010
	ESR	0.06	0.820	-0.26	0.740	0.08	0.750	0.69	< 0.001	0.77	< 0.001
	Sand	-0.24	0.340	-0.85	0.150	-0.27	0.270	0.15	0.370	0.22	0.200
	Clay	-0.02	0.950	-0.04	0.960	-0.10	0.680	0.21	0.220	0.07	0.680

lower levels of OM at 0–0.1 m (Table 3).

3.2. Irrigation water quality and its relationship with changes in soil properties

The proposal by Costa and Aparicio (2015) that adjusts the SAR values of water according to the use of irrigation and rainfall, showed, in general, better correlations with the chemical and physical properties of the soils than the SAR without the adjustment by the dilution factor and in comparison with the levels of cumulative irrigation. The SARdf correlated positively with bulk density, the largest soil fragments measured by the drop shatter test, EC, pH and the ESR levels in the 0–0.10 m and 0–0.20 m soil layers. In contrast, it correlated negatively with infiltration and the smallest soil fragments measured by the drop shatter test (Table 4).

The threshold value of 3.5 for the SARdf proposed by Costa and Aparicio (2015) can be considered excessive for the conditions evaluated in this work. In the relationships observed between SARdf and ESR, bulk density and basic infiltration levels for the available data, the SARdf value of 3.5 determines ESR levels greater than 3.0%, Bd 0–5 levels greater than 1.32 Mg m^{-3} and reductions in basic infiltration greater than 65% (Fig. 4).

In the Pampas region, rainfall variations associated with climate change have been reported, with ranges higher than 800 to 1100 mm $year^{-1}$ (Bernal-Mujica et al., 2023) and complementary irrigation requirements in wheat of 100 mm $year^{-1}$ (Lavado, 2009). The SARdf made it possible to plan complementary irrigation based on expected infiltration reductions according to variations in SAR levels and rainfall. Table 5 shows an example of complementary irrigation planning based on SARdf. The annual irrigation average was defined according to SAR levels of 4, 10 and 16, average rainfall of 800, 950 and 1100 mm $year^{-1}$, and infiltration reduction limit values of 50, 60 and 70%. Assuming a need for irrigation in wheat of 100 mm $year^{-1}$, the number of years that a crop may be irrigated over a 10-year period was estimated.

In irrigation water scenarios with high RAS or in climate change scenarios with rainfall modifications, the use of SARdf can help producers plan the proper management of complementary irrigation. The irrigation water quantity limit to be used can be defined using SARdf.

The available data allowed us to correlate the relationship between sodium input from irrigation with the increases in ESR levels of the soils and the deterioration of physical properties. In the evaluated conditions, the reduction in basic infiltration levels and the increases in Bd 0–5 with higher ESR levels were independent of other soil properties. However, in the Pampas region Typic Argiudolls, differences in sodium affinity have been reported in connection with soil texture (Aparicio et al., 2014). In turn, different management practices can be expected to enhance the resilience of physical parameters in the face of changes in the ESR. These factors should be considered for the use of SARdf in complementary

Table 5
Proposal for annual average irrigation, total cumulative irrigation over 4 years and number of years with optional wheat irrigation every 10 years according to the sodium adsorption ratio (SAR) of irrigation water, average expected annual rainfall and expected infiltration reduction; 100 mm $year^{-1}$ was considered to be the complementary irrigation requirement for wheat (*Triticum aestivum L.*) cultivation.

SAR	Expected rainfall (mm $year^{-1}$)	Expected infiltration reduction (%)	Annual average irrigation (mm)	Total cumulative irrigation over 4 years (mm)	Years with wheat irrigation every 10 years
0		50%	48	192	5
	800	60%	126	504	10
		70%	430	1720	10
4		50%	55	220	6
	950	60%	140	560	10
		70%	550	2200	10
0		50%	65	260	7
	1100	60%	160	640	10
		70%	600	2400	10
0		50%	7	28	1
	800	60%	19	76	2
		70%	50	200	5
10		50%	9	36	1
	950	60%	21	84	2
		70%	58	232	6
0		50%	10	40	1
	1100	60%	24	96	2
		70%	67	268	7
0		50%	3	12	0
	800	60%	7	28	1
		70%	18	72	2
16		50%	4	14	0
	950	60%	8	32	1
		70%	22	88	2
0		50%	4	16	0
	1100	60%	9	36	1
		70%	25	100	3

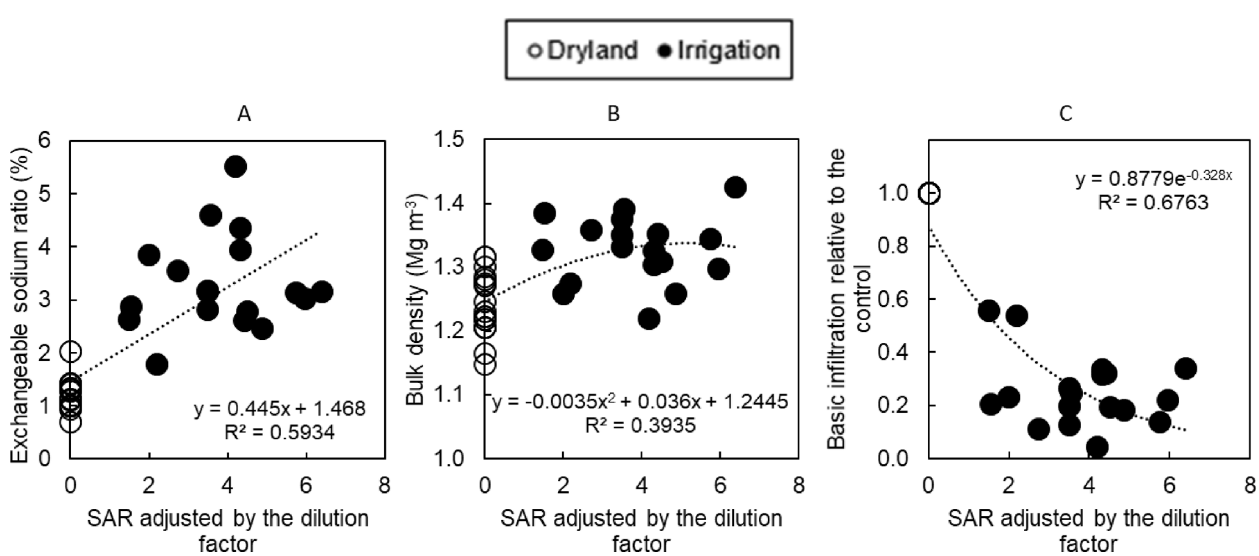

Fig. 4. A: relationships between exchangeable sodium levels (%), B: bulk density in the 0–0.05 m soil layer, C: average basic infiltration relative to the control, according to the sodium adsorption ratio of irrigation water (SAR) adjusted by the dilution factor (Costa and Aparicio, 2015). Data correspond to the soils of 46 sites (23 dryland + 23 irrigated) in the Pampas region (Argentina).

irrigation planning and in future studies.

4. Conclusions

In Typic Argiudolls from the Pampas region with initial ESR levels lower than 2.0%, the complementary irrigation (water with SAR levels from 0.9 to 18.9) increases the surface bulk density by 6% and reduces the infiltration rate by 52%.

The changes in bulk density and infiltration rate of Typic Argiudolls under complementary irrigation are closely related with changes in the ESR values measured in the 0–0.20 m depth layer.

Furthermore, changes in soil physical properties are directly related to irrigation water quality based on SAR values adjusted by the rain dilution factor.

Under the frequent environmental and crop management conditions of sub-humid temperate regions and with the purpose of an enhanced design of complementary irrigation practices it is advisable to avoid the application of water when the corrected SAR (SARdf) values are greater than 3.0.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

Alvarez, C.A., Rimski Korsakov, H., Torres Duggan, M., 2021. Effects of supplementary irrigation on soils and crops in sub-humid areas in the Pampas Region of Argentina. In: Taleisnik, E., Lavado, R.S. (Eds.), Saline and Alkaline soils in Latin America: Natural Resources, Management and Productive Alternatives, Springer Nature, pp. 285-294.

Andriulo, A., Galetto, M.L., Ferreira, C., Cordone, G., Sasal, C., 1998. Efecto de 11 Años de riego complementario sobre un Argiudol típico Pampeano. Ciencia del Suelo 16, 125–127.

Angelini, H.P., Costa, J.L., Aparicio, V.C., 2022. Expansión del riego: Tipo de suelo, pendiente y calidad de agua en el sudeste de la provincia de Buenos Aires. Faculty Agron. J., La Plata 121 (1), 1–14.

Aparicio, C.V., Barbacone, A., Costa, J.L., 2014. Efecto de la calidad de agua para riego complementario sobre algunas propiedades químicas edáficas. Ciencias del Suelo 32 (1), 95–104.

Ayers, R.S., Westcot, D.W., 1987. Water quality for agriculture. Irrigation and drainage notebooks 29. FAO. Roma.

Bernal-Mujica, A., Lovino, M.A., Müller, G.V., Pierrestegui, M.J., 2023. Spatiotemporal variability of extreme precipitation events and their impacts on soil moisture and water table depth in Argentina's core crop region. Hydrol. Sci. J. 1–16.

Costa, J.L., Aparicio, V.C., 2015. Quality assessment of irrigation water under a combination of rain and irrigation. Agric. Water Manage. 159, 299–306.

De Battista, J.J., Andriulo, A., Pecorari, C., 1993. El perfil cultural: un método para la evaluación de sistemas de cultivo. Ciencia del Suelo 10, 89–93.

Díaz-Zorita, M., Perfect, E., Grove J.H., 2002. Disruptive methods for assessing soil structure, Soil and Tillage Research, 64, 3-22.

Galindo, G., Sainato, C., Dapeña, C., Fernandez-Turiel, J.L., Gimeno, D., Pomposiello, M., Panarello, H., 2007. Surface and groundwater quality ion the northeastern region of Buenos Aires Province, Argentina. J. S. Am. Earth Sci. 23 (4), 336–345.

Lavado, R.S., 2009. Salinización y sodificación de suelos de producción agrícola extensiva por riego complementario. In: Taboada, M.A., Lavado, R.S. (Eds.), Alteraciones de la fertilidad de los suelos, FAUBA editor. pp. 163.

Levy, G.J., Levin, J., Shainberg, I., 1997. Prewetting rate and aging effects on seal formation and interrill soil erosion. Soil Sci. 162 (2), 131–139.

Mon, R., Irurtia, C., Botta, F.G., Pozzolo, O., Bellora Melcón, F., Rivero, D., Bomben, M., 2007. Effects of supplementary irrigation on chemical and physical soil properties in the Rolling Pampa region of Argentina. Ciencia e Investigación Agraria 34, 143–150.

Mueller, L., Shepherd, G., Schindler, U., Ball, B.C., Munkholm, L.J., Hennings, V., Smolentseva, E., Rukhovic, O., Lukin, S., Hu, C., 2013. Evaluation of soil structure in the framework of an overall soil quality rating. Soil Tillage Res. 127, 74–84.

Nelson, D.E., Sommers, L.E., 1996. Total carbon, organic carbon, organic matter. 961-1010 p. In: JM Bigham (eds). Methods of Soil Análisis (part 3). ASA and SSA, Madison. WI. USA.

Peralta, G.E., 2008. Estructura de suelos manejados en siembra directa: efectos sobre la extracción y conversión de agua en el cultivo de soja (*Glycine max L. Merril*). Thesis presented to opt for the title of Doctor of the University of Buenos Aires, Agricultural Sciences Area. 291 pp.

Pilatti, M.A., Imhoff, S., Ghiberto, P., Marano, R., 2006. Changes in some physical properties of Mollisols induced by supplemental irrigation. Geoderma 133, 431–443.

SAMLA, 2004. Methodological Support System for Soil, Water, Vegetable and Organic Amendments Analysis Laboratories: water analysis. 1st edition. SAGyP. Agriculture Directorate. CD ROM.

Soil Quality Institute, 1999. Soil Quality test kit guide. NRCS Soil Quality Inst, Auburn, AL.

Soil Survey Staff, 2022. Keys to Soil Taxonomy. 13th ed. Natural Resources Conservation Service. U.S. Department of Agriculture Handbook, pp. 402.

Suarez, D., Wood, J., Lesh, M., 2006. Effect of SAR on water infiltration under a sequential rai-irrigation management system. Agric Water Manag 86, 150–164.

Suarez, D.L., Wood, J.D., Lesch, S.M., 2008. Infiltration into Cropped Soils: Effect of Rain and Sodium Adsorption Ratio-Impacted Irrigation Water. J. Environ. Qual. 37, 169–179.

Torres Duggan, M., Álvarez, C.R., Taboada, M.A., Celesti, T., Vignarolli, F., ĎAmbrosio, D., 2012. Riego complementario en un Argiudol Tipico de la Pampa Ondulada Argentina bajo siembra directa: efectos sobre algunas propiedades químicas y físicas del suelo. Ciencias del suelo, 30(2),201-207.